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FROM SED HI CONCEPT TO PLEIADES FM DETECTION UNIT MEASUREMENTS

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ABSTRACT

The first flight model PLEIADES high resolution instrument under Thales Alenia Space development, on behalf of CNES, is currently in integration and test phases.
Based on the SED HI detection unit concept, PLEIADES detection unit has been fully qualified before the integration at telescope level. The main radiometric performances have been measured on engineering and first flight models.

This paper presents the results of performances obtained on the both models. After a recall of the SED HI concept, the design and performances of the main elements (charge coupled detectors, focal plane and video processing unit), detection unit radiometric performances are presented and compared to the instrument specifications for the panchromatic and multispectral bands. The performances treated are the following:
- video signal characteristics,
- dark signal level and dark signal non uniformity,
- photo-response non uniformity,
- non linearity and differential non linearity,
- temporal and spatial noises regarding system definitions

PLEIADES detection unit allows tuning of different functions: reference and sampling time positioning, anti-blooming level, gain value, TDI line number. These parameters are presented with their associated criteria of optimisation to achieve system radiometric performances and their sensitivities on radiometric performances.
All the results of the measurements performed by Thales Alenia Space on the PLEIADES detection units demonstrate the high potential of the SED HI concept for Earth high resolution observation system allowing optimised performances at instrument and satellite levels.

1. INTRODUCTION

SED HI concept has been chosen to be applied on the PLEIADES High Resolution optical instrument dedicated to earth observation.
This detection unit is a combination of new developments from visible sensors based on Charge Coupled Devices (CCD) to focal plane assembly and video unit. The main characteristic of the SED HI architecture is a high level of integration where all analogue and digital signal processing's are localised as close as possible to the CCDs to take into account video frequencies up to 7 MHz and 70 video channels. This architecture has allowed to minimise noise and to optimize radiometric performances and interface budgets (mass, volume, power consumption).

The following paragraphs recall a technical description of the main elements of the SEDHI which has been used for the PLEIADES instrument, present the main requirements and detail the electrical and radiometric performances which have been measured at detection unit and instrument levels and provide the budgets for the flight model complete detection subsystem.

2. DESIGN DESCRIPTION AND MAIN REQUIREMENTS

2.1 Focal plane assembly

Focal plane assembly has been developed under TAS contract by SODERN [5]. The design of the focal plane assembly has demonstrated a high level of mechanical integration to allow the use of 10 CCDs modules based on 5 Panchromatic CCDs / 5 XS (Multi-Spectral) CCDs and their associated proximity electronics. This concept allows to obtain on board a continuous lines for each spectral band. It is based on a SiC mechanical structure about 400mm length and a SiC central mirror [6]. Two CCDs per spectral bands are illuminated through optical reflections on SiC central mirror and splitting plane mirrors (~80mm length). Three CCDs

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are directly illuminated after a single reflection on the SiC central mirror.

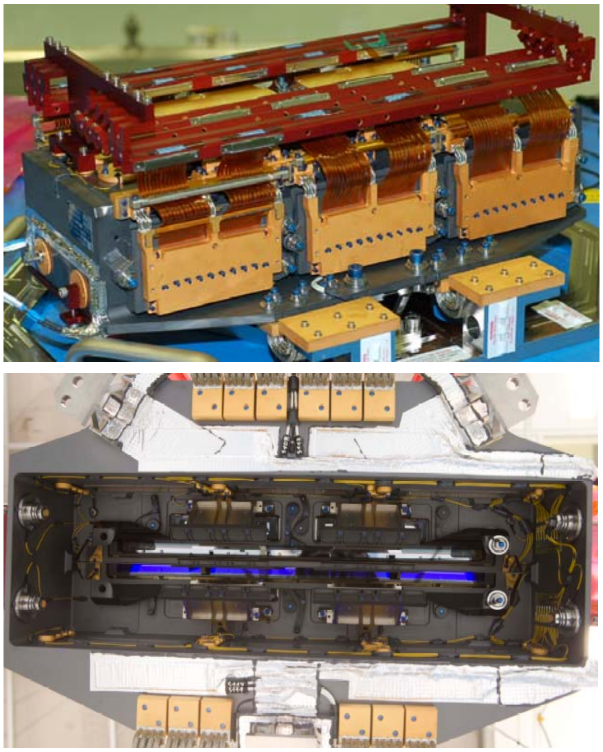

Fig. 1. Views of the PLEIADES Focal Plane Assembly (top and bottom faces)

The thermal concept has been optimised in order to minimise temperature drift during the maximum duration of pictures (~ 4°C). It involves that the error on the dark signal level regarding temperature influence in flight is minimised and will allow excellent detection unit spatial noise.

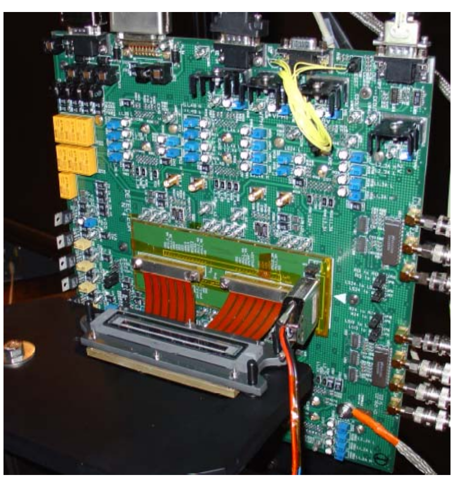

Fig. 2. View of equipped CCD module under electrical tests with Thales Alenia Space specific electrical interface board.

2.2 Panchromatic and Multispectral Charge coupled devices

The main characteristics of the CCDs used in the PLEIADES detection subsystem have been presented respectively in [3] and [4] for Panchromatic (PAN) and multispectral (XS) CCDs.
The table hereafter summarises all performances measured on flight model devices.

Table 1. PAN and XS CCDs main measured performances

	PAN CCD 98-50	MS CCD AT-71554
Pixel number	6000*20 TDI separated in 10 registers	4 lines*1500
Pitch	13µm	52µm
Spectral band	480 – 820 nm	B0 :450 – 530 nm B1 : 510 – 590 nm B2 : 620 – 700 nm B3 : 775 – 915 nm
Operating pixel frequency	6.6MHz	3.76 MHz
Functions	TDI	Register binning
Qsat	130ke	330ke
Dark noise	130µV rms	120-170µV rms
Vdark	4µV per TDI stage	45µV
DSNU p-p (register)	15µV	11µV
PRNU p-p	<5%	<3%
Non linearity	<1,5%	<1%
Responsivity (V/µJ/cm²)	> 11.3	B0 = 360 B1 = 264 B2 = 261 B3 = 298

The PLEIADES CCDs have been developed specifically for PLEIADES instrument. After several years from prototypes to flight models delivery the capability of performances have been fully demonstrated. These high levels of performances are one of the main contributors of the FM detection unit electrical and radiometric performances level.

All these performances have been measured by the E2V company in charge of the CCDs development and Thales Alenia Space with dedicated test bench having optical interfaces representative to those of Pleiades instrument.

Fig. 3. View of PAN CCD 98-50

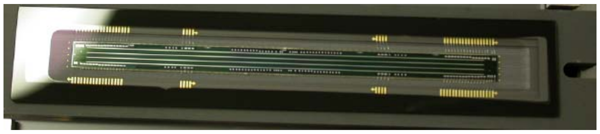

Fig. 4. View of XS AT-71554

CCD 98-50 dedicated to panchromatic spectral band is a back-thinned TDI with a photomos pixel structure including an anti-blooming.
The silicon epitaxial layer thickness has been optimized to ensure an optimum trade-off between quantum efficiency and modulation transfer function.
The photosensitive line is delimited by a storeshield deposited on the back face preventing from parasitic light.
The AT-71554 for multispectral band is composed of 4 front illuminated lines with photodiode pixel structure.
The two devices use the same co-fired Aluminum Nitride type of hermetic package with a BaK50 window.

2.3 Multispectral stripped filters

Multispetral filters have been a key development to allow a perfect spectral response of the instrument. Stripped spectral filters are directly glued on the XS CCD package.

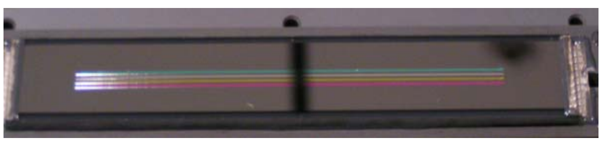

Fig. 5 View of stripped multispectral filters glued on CCD AT 71554

Two functions are fulfilled by the stripped spectral filters:

- optical diaphragm to eliminate any parasitic light using an absorbing layer between filter lines
- spectral filters optimized regarding spectral response template. Specific attention has been taken to minimize the spectral response dispersion (SRD) along the filters. This performance is a strong contributor of the spatial noise budget and must be reduced.

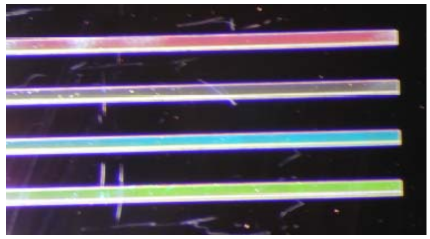

Fig. 6. View of optical coatings used on stripped multispectral filters

2.4 Video Electronic Unit

Video electronic unit is a dedicated development by Thales Alenia Space based on SED HI concept [2] using several analogue customised hybrids. The main characteristics are presented in Table.2.

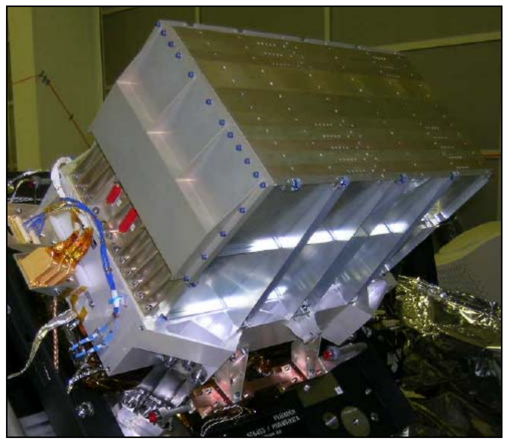

Fig. 7 View of the Video Unit fully integrated on its dedicated mechanical support ready for EMC environment tests.

Fig. 8. View of a Video Unit Board coupled with a CCD module during electrical tests.

FAST and TRIM Asics designed and developed for the CCD hybrid driver have allowed a fine tuning of the CCD timing. CLBNG Asic dedicated to analog video processing has been demonstrated at 12 bits resolution (ENOB) up to 10 MHz.
The use of all these Asics have allowed to reach a high level of integration and performances for the video electronic unit.

Table 2. Electronic video unit main performances

Board number / video chain number	5 PAN video boards 5 XS video boards / 70 video chains
ADC resolution	12 bits
Maximum operating frequency	10 MHz
Noise performance	1.2lsb
Integral Non Linearity	<1.6lsb
Differential Non Linearity	<1.2lsb
Mass	18kg
Static Power consumption	220W

3. FM DETECTION UNIT PERFORMANCES

3.1 Electrical performances

Electrical performances of Detection Unit are mainly due to the quality of the video and reference signals sampled in video electronics. Most important characteristics are width and flatness of the video steady-state signal.

PLEIADES video electronic unit characteristics allow high tolerance in the location of the sampling instants. Video and reference signal sampling instants are defined so that evolution due to temperature drift and ageing do not distort the performances at electronic output such as noise or signal slope.

The signal widths available for sampling on PAN and XS video signal are the following:

Table 3. Sampling window

	PAN	XS
Video signal	> 20 ns	> 11 ns
Reference signal	> 40 ns	> 40 ns

Fig. 9. displays time window available for signal sampling under irradiance level.

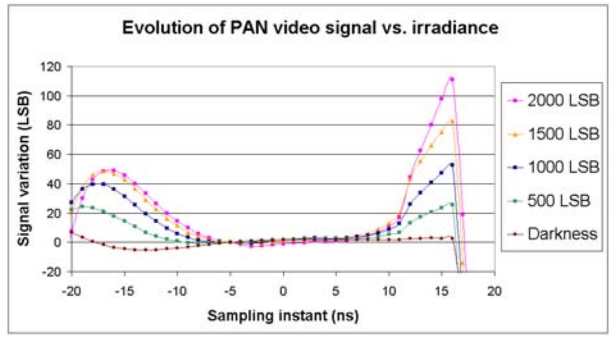

Fig. 9. Example of PANchromatic video signal

Drift of sampling instant leads to a maximum signal level variation of 0.3 LSB for XS spectral bands and 0.5 LSB for the PANchromatic band at CCD output.

3.2 Radiometric performances

3.2.1 Main contributors

Main radiometric performances of detection unit are the following:

Temporal noise

Temporal noise transposes noise appearing at high frequency on successive identical image takes. This noise is computed for each pixel of the detection line as the standard deviation on 50 successive images.

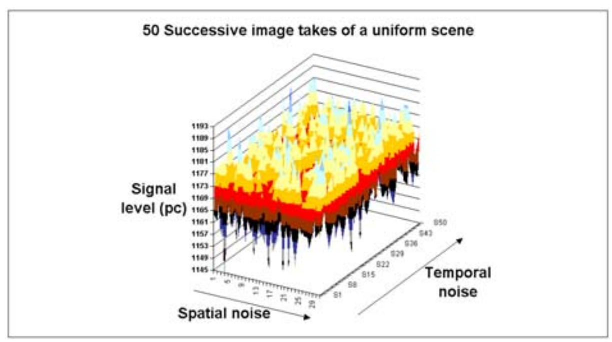

Fig. 10. Example of successive PANchromatic images of a uniform scene

Performances of temporal noise measured on PLEIADES instrument are given in the following table.

Table 4. Temporal noise performances @ Iref

Spectral Bands	PAN	B0	B1	B2	B3
Measurements (LSB)	7.6	8.1	7.6	7.3	7.9
Requirements (LSB)	18.1	19.9	18.5	17.2	23.5

Fig.11, and Fig.12. illustrate temporal noise level in panchromatic and B2 spectral bands along the instrument swath.

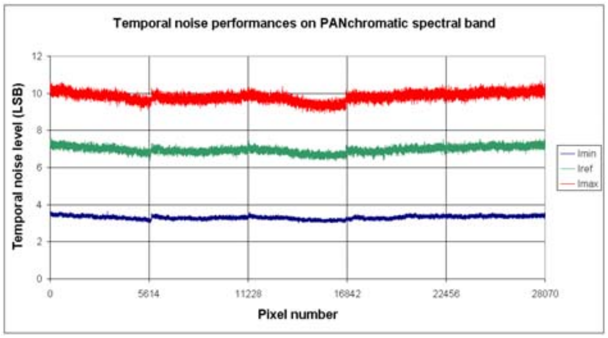

Fig. 11. Temporal noise on PAN spectral band (exc. inter-CCD areas)

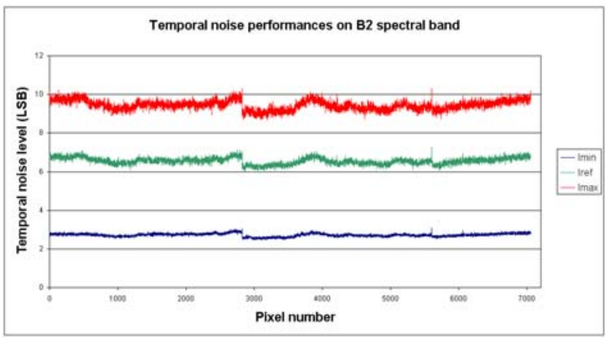

Fig. 12. Temporal noise on B2 spectral band (exc. inter-CCD areas)

Performances of temporal noise are directly related to the signal-to-noise ratio that describes the useful signal level relative to the background noise level. Combination of high-performance electronic unit and detectors allow PLEIADES detection unit to reach very high performances of signal-to-noise ratio relatively to requirements in panchromatic and multispectral bands.

Dark signal levels and dark-signal non-uniformity

The temporal drift of darkness non-uniformity of the CCD along the detection line between the calibration image and the useful image is one of the contributor to the spatial noise.

Flight radiometric equalization is processed with parameters computed on a "calibration" image with a specific darkness image taken at a given instant (temperature, irradiation level…). Once a useful image is taken, environment may have changed and have induced a drift in the darkness propriety of the CCD. Maximum drift may achieve a 10-factor between the both images on multispectral bands and a 2-factor on panchromatic band and thus may induce spatial noise on the image.

Dark signal instrument level is driven mainly by the electronic offset, about 31.5 LSB and lesser by the CCD offset, about 0.5 to 2 LSB respectively on panchromatic and multispectral CCD. CCD dark signal increase due to irradiation or temperature may reach a factor 2 to 4 respectively on PAN and XS CCD. Therefore dark signal do not exceed 3% of the whole signal dynamics which is the mission requirement.

Photo-Response Non Uniformity (PRNU)

PRNU is the difference in response between the most and least sensitive elements of the whole detection line of the instrument. Improvement of PRNU allows better spatial noise performances. PLEIADES PRNU performances are presented in the table below.

Table 5. PRNU Performances of PLEIADES

PRNU peak-to-peak	PAN	B0	B1	B2	B3
Performances	5%	18%	19%	21%	15%
Requirements	30%				

Detection unit PRNU performance is mainly driven by CCD PRNU performance and by the spectral filter transmission non-uniformity in the case of multispectral bands.

Non-linearity and differential non-linearity

Differential non-linearity between each chain of the detection unit constitutes one of the most important contributors to the spatial noise. Differential non-linearity performance of the detection unit is the combination of several contributors:

- Differential non-linearity between the electronic chains (in the VEU and the focal plane assembly for proximity electronics);
- Differential non-linearity between the several CCDs of the detection line;
- Differential non-linearity between pixels of a singular CCD.

Performances of global differential non-linearity along the detection line are introduced in Fig. 13 for different irradiance levels.

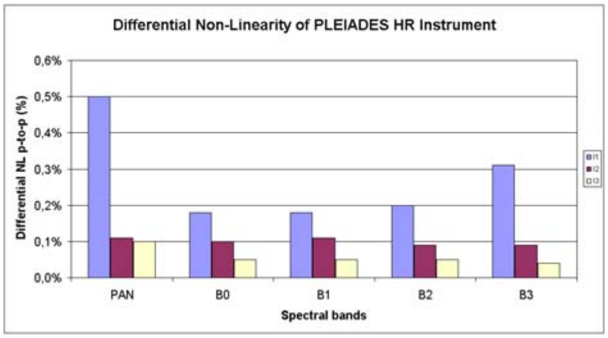

Fig. 13. PLEIADES HR performances of NLdiff (exc. inter-CCD areas) @Imin, Iref and Imax

At low irradiances, performance of differential non-linearity is mainly due to the differential non-linearity of electronics. This phenomenon is accentuated on the panchromatic spectral band as each CCD is split into 10 registers that have their own video chain.

Table 6. PLEIADES HR performances of NLdiff (exc. inter-CCD areas)

Irradiance	PAN	B0	B1	B2	B3
Imin	0,50%	0,18%	0,18%	0,20%	0,31%
Iref	0,11%	0,10%	0,11%	0,09%	0,09%
Imax	0,10%	0,05%	0,05%	0,05%	0,04%

Note: Imin-Imax is defined as the maximum irradiance dynamic on which radiometric performances shall be achieved.

NLdiff performance is one of the main contributor to spatial noise. Design during PLEIADES development has been done in order to reduce at most NLdiff level.

Non-linearity of detection unit represents distorsion of output signal with respect to the input signal. Performances of NL are computed as following:

$$\forall\, I1, I2 \in [I\min, I\max]$$
$$NL(\%) = \left| 1 - \frac{S(I1)}{I1} \cdot \frac{I2}{S(I2)} \right| \quad (1)$$

Where *I1*, *I2* is any couple of irradiances taken into [*Imin*,*Imax*] dynamic. *S* is defined as the mean of equalized radiometric signal over detection line.

PLEIADES NL performances are presented below.

Table 7. PLEIADES maximum absolute non linearity performances

Maximum NL	PAN	B0	B1	B2	B3
	0.98%	0.28%	0.22%	0.31%	2.9%
Requirements	5%				

Requirements are widely achieved thanks to the very low non-linearity reached by CCD themselves.

3.2.2 SNR performances

SNR is the ratio between useful signal level after equalization and temporal noise. An example is given in the following figure:
Fig.14. displays minimum performances measured over the whole detection line at reference irradiance:

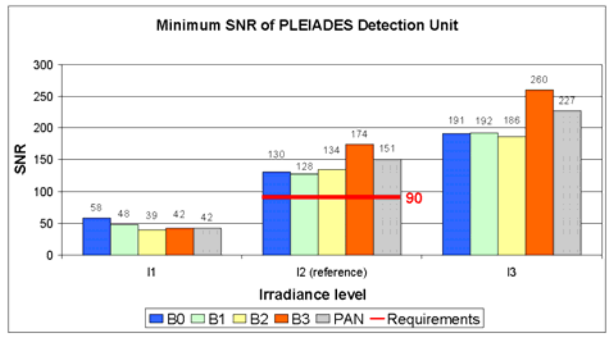

Fig. 14. SNR PLEIADES Detection Unit Performances

Table 8. Minimum SNR Performances at different irradiances

Spectral bands	PAN	B0	B1	B2	B3
Iref	151	130	128	134	174
Iref requirements	90				

Performances are widely above mission requirements at reference irradiances. Moreover high performances at low irradiances can be pointed out : high convenience is thus provided to observe low illuminated scenes.

3.2.3 Spatial noise performances

Image equalization is not perfect and residual noise remaining on the image in the spatial direction (Fig.15. and Fig.16.) is called spatial noise.

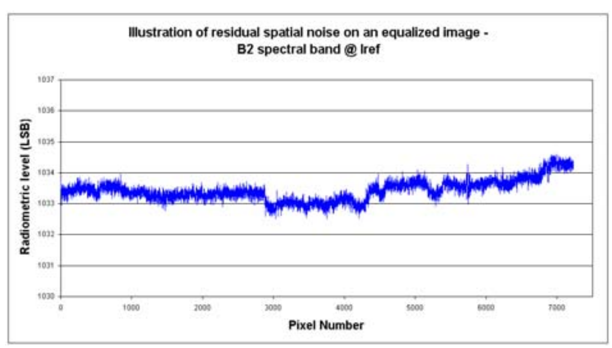

Fig. 15. B2 Image after equalization @ Iref

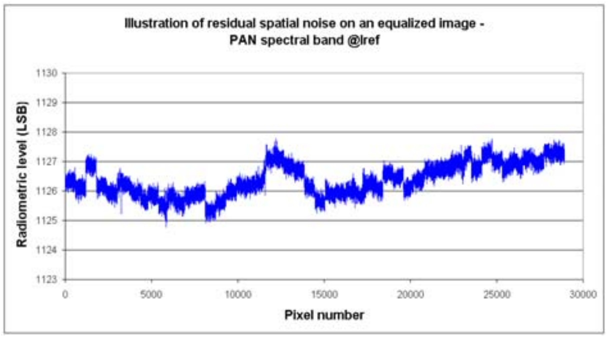

Fig. 16. PAN Image after equalization @ Iref

Spatial noise is due to spectral, electronics and detectors contributors.

The large amount of CCDs multiplied by the number of video chains inside the focal plane assembly and the video electronic unit contribute to the occurence of potential spatial noise along the detection line.

Evaluation of spatial noise on ground does not take into account the spectral contributor as it depends on the spectral content of the scene. Performances of spatial noise on-ground have been evaluated in front of a uniform scene that do not make appear spectral dispersion.
Therefore performances measured on-ground are mainly due to inherent performances of detectors and video electronics.

Spatial noise is thus the combination of video unit chain differential non-linearity, darkness performances and drifts involved by the environment between calibration and take of a useful image.
Spatial noise is defined as the high-frequency noise along spatial direction. It is evaluated as the maximum difference peak-to-peak of radiometric signal at detection unit output over a 50-adjacent-pixel window:

$$\begin{aligned}&\textit{for } c = 1 \textit{ to } N-49,\\&\Delta m = \left(\max_{i=c\ldots c+49}(S(i)) - \min_{i=c\ldots c+49}(S(i))\right)\end{aligned} \qquad (2)$$

With N the number of pixels on the detection line and $S(i)$ the equalized radiometric signal of pixel i.

Fig.17. and Fig.18. show performances of spatial noise measured on-ground. As explained above, these measurements do not take into account noise due to spectral contributor.

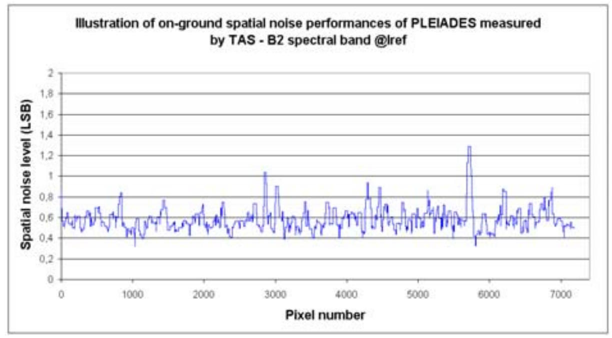

Fig. 17. Spatial noise @ Iref on B2 spectral band

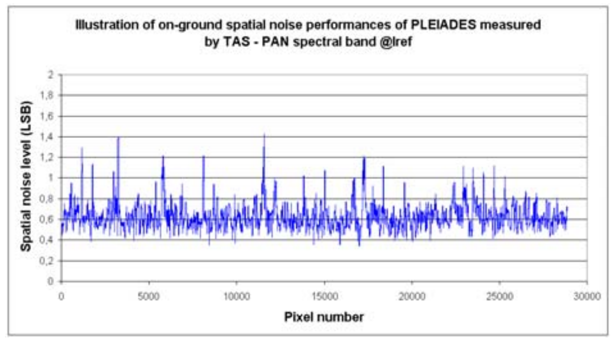

Fig. 18. Spatial noise @ Iref on PAN spectral band

Blue graph represents spatial noise along the detection line of B2 and PAN spectral bands. Excluding inter-CCD areas, maximum of spatial noise is about 1.1 LSB for a signal level of 1150 LSB.

Spectral contributor to the spatial noise is the noise induced by the "spectral response dispersion" (SRD) on 50 pixels window. Each pixel has its own spectral response that may differ from one pixel to another and thus induces spatial noise between adjacent pixels when viewing the same scene in term of spectral content [4], but a scene different from the calibration scene.

SRD performance has a significant impact on the global performance of the instrument on-flight and can become the main contributor of spatial noise. Impact is more important in the case of multispectral bands that have narrow spectral responses, much more sensitive to a drift or a difference of spectral slope and its impacts in front of different landscapes.

Particular cautions have been taken during detection unit development to reduce at most the contributions of CCD and electronics differential non-linearity impacts, among other, on spatial noise in order to fulfil requirements when taking into account SRD contribution.

Table.9. and Table.10. present respectively the ratio between spatial noise and temporal noise:
- the performance measured by Thales Alenia Space on PLEIADES on ground (without SRD contribution),
- the estimation on flight, including SRD contribution measured on spectral filters.

Table 9. . Typical spatial noise performances versus temporal noise on PLEIADES measured on-ground (exc. SRD)– Center of detection line

	PAN	B0	B1	B2	B3
Imin	0.2	0.1	0.1	0.1	0.1
Iref	0.2	0.1	0.2	0.1	0.2
Imax	0.2	0.1	0.1	0.1	0.1
Spatial noise Requirement	< 2	< 2	< 2	< 2	< 2

Table 10. Typical beginning of life spatial noise performance versus temporal noise estimation on PLEIADES (inc. SRD)– Center of detection line

	PAN	B0	B1	B2	B3
Imin	0.8	0.3	0.5	0.3	0.1
Iref	1.7	0.3	1.4	0.7	0.4
Imax	1.5	0.3	1.6	0.6	0.4
Spatial noise Requirement	< 2	< 2	< 2	< 2	< 2

PLEIADES detection unit performances fulfil requirements thanks to a highly inherent performance of the detection electronics and CCD, and despite high impact of SRD on the global performances.

Worst budgets of spatial noise performances at end of life are fully compliant with the requirements.

4. CONCLUSIONS

All performances measured on the FM detection unit will allow outstanding performances at system level with a real margin regarding the requirements.
This development of an operational detection system by Thales Alenia Space for PLEIADES instrument with such high radiometric performances demonstrates the potential of the SED HI concept. The high level of integration of all the key functions between detectors and video unit is the unique way to master high radiometric performances with high video frequency and large number of video chains.
Based on SED HI concept, Thales Alenia Space has prepared and is currently involved in the development of a new generation of detection unit for the future generation of earth observation high resolution optical instrument.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. Lamard J.L., Gaudin-Delrieu C., Valentini D., Renard C., Tournier T., Lahererre J.M., *Design of the high resolution optical instrument for the PLEIADES HR earth observation satellites* , ICSO 2004.
2. Dantes D., Biffi J.M., Neveu C., Renard C., *SED HI : Development status of the PLEIADES detection electronics*, ICSO 2004.
3. Materne A., Bardoux A., Geoffray H., Tournier T., Kubik P., Morris D., Wallace I., Renard C., *Backthinned TDI CCD image sensor design and performance for the PLEIADES High Resolution Earth Observation Satellites*, ICSO 2006.
4. Geoffray H., Loesel J., Loiret I., Quicot J.J., *Long quadrilinear CCD sensors equipped with long linear filters: Characteristics and performances for the multispectral channel of Earth observing systems*, SPIE Vol. 5978, , 2005.
5. Le Goff R., Pranyies P., Toubhans I., *Focal Plane Assembly AIT sequence: evolution from HRG-Spot 5 to PLEIADES HR*, ICSO 2006.
6. Pranyies P., Deswarte D., Toubhans I., Le Goff R., *SiC focal plane assembly for the Pleiades HR Satellite*, SPIE Vol. 5570, p. 568-576, 2004.
7. Materne A., Gili B., Laubier D., Gimenez T., *Quadrilinear CCD sensors for the multispectral channel of spaceborne imagers*, SPIE Vol. 4540, p. 309-317, 2001.